

Research Article

An Evolution Analysis of Collaborative Innovation Network considering Government Subsidies and Supervision

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Collaborative innovation networks have the basic attributes of complex networks. The interaction of innovation network members has promoted the development of collaborative innovation networks. Using the game-based theory in the B-A scale-free network context, this paper builds an evolutionary game model of network members and explores the emergence mechanism from collaborative innovation behavior to the macroevolution of networks. The results show that revenue distribution, compensation of the betrayer, government subsidies, and supervision have positively contributed to the continued stability of collaborative innovation networks. However, the effect mechanisms are dissimilar for networks of different scales. In small networks, the rationality of the revenue distribution among members that have similar strengths should receive more attention, and the government should implement medium-intensity supervision measures. In large networks, however, compensation of the betrayer should be attached greater importance to, and financial support from the government can promote stable evolution more effectively.

1. Introduction

With the acceleration of technology advances, technology innovations are becoming more complex, and enterprises can scarcely adapt to increasingly complex market demands relying only on independent innovation. Innovative enterprises join in collaborative innovation because they can share risks, complementary resources, and benefits [1]. Collaborative innovation aims to integrate resources by concentrating the advantages of heterogeneous innovative enterprises [2]. With further developments, innovation gradually evolved from linear to multiagent collaborations. Innovation networks emerged as a new form of organization [3, 4]. The cooperative relationships among the network members are the main connections, based primarily on contracts and on innovative activities to maximize the interests of all participants [5]. Drawing on Freeman's research [6], this paper argues that collaborative innovation networks are open networks with clustering and knowledge spillover advantages based on long-term stable interfirm interactions and synergy among formal and informal network members.

Today, collaborative innovation networks in some developed countries are mature. For example, in Silicon Valley,

innovative enterprises, research universities, institutions, industry associations, and service enterprises are connected closely [7], exploiting their mutual advantages and achieving collaborative innovation. In some developing countries, however, collaborative innovation networks are at early stages of development [8]. Unstable synergy, uneven distribution of interests, betrayal in the halfway, and the "free rider" have led to disintegration of collaborative innovation networks. Therefore, in some countries, governments have introduced incentive policies to maintain the stable development of collaborative innovation networks, providing support and supervision for the collaborative innovation process; the aims of these policies are to effectively reduce the number of opportunists and the pre- and posttransaction costs of collaborative innovation to ensure the stability of the networks. Some questions arise with regard to these processes. For instance, what are the main factors that affect the development of collaborative innovation networks? What are the differences in the impacts of these factors on the evolution of collaborative innovation networks of different scales? How can the government formulate policies to effectively promote the development of collaborative innovation networks?

The aim of this paper is to explore the collaborative innovation behavior of network members and study how these collaborative innovation networks evolve based on micro-actor behavior. The intent is to explain how revenue distribution, compensation, and government policies play roles in the evolution of different scales of collaborative innovation networks. This paper is structured as follows. Section 2 reviews the theory of collaborative innovation networks. Section 3 shows the research methods of this paper. Section 4 analyzes the results of the simulation, and Section 5 summarizes this paper.

2. Literature Review

Collaborative innovation networks are the main topic in this paper. After reviewing some recent research, we found that the main fields of related work focused on the characteristics of the collaborative networks members (micro), the evolution processes of the networks (macro), and the networks' collaborative performance. We report some of our findings below.

In terms of the works on members of in collaborative innovation networks, social network analysis is the main method to study the characteristics of network nodes and the relationships between them. Landart et al. found that innovation networks that are well managed can provide many benefits to enterprises [9]. Dhanaraj studied the activity and openness of network nodes and found that the core members of innovation networks can coordinate overall network actions to achieve the effects of collaborative innovation [10]. Tsai pointed out that if enterprises occupy the center of the networks, they can generate more innovations. Tseng analyzed centrality and density of firms in the innovation networks, and found that the higher centrality and higher density, the stronger innovation capability [11].

The research on the evolution of innovative networks mainly focuses on network topology and its influencing factors. Woo found that the connection mechanism has a great impact on network evolution using social network analysis to study the dynamic evolution of high-tech innovation networks [12]. Fleming analyzed the impacts of core firms on the evolution of innovation networks and thought that core innovation network members are important factors that drive the network to centralize [13]. Lazzeretti investigated the impact of neighborhood on innovation network dynamics [14]. Liang explored the evolution of collaboration network within government sponsored and found that network structure and composition should be involved into the specific policies [15].

In terms of collaborative innovation performance, most researchers focused on the factors affecting performance. In summary, the main factors affecting performance are network structure (network density [16], clustering coefficient [17], average path length [18], openness [19]), connections between network nodes (contact directness, number, intensity, content, etc. [20, 21]), and network governance mechanisms (contracts and rules such as resource allocation and incentive constraints that restrict and regulate behavior of the nodes [22, 23]).

The abovementioned studies are all in-depth investigations of collaborative innovation networks; the authors put forward many models and research methods, which are a great contribution to the field of collaborative innovation network studies. However, there are three issues that need to be explored deeply: (1) there is little literature concerning the emergence mechanism from innovation network member behavior to macroevolution; (2) there is also little literature that focuses on the stable evolution of collaborative innovation networks; (3) network governance mostly focuses on the constraints and adjustments under the market mechanism. It is necessary to further study the impacts of government policies on the evolution of collaborative innovation networks. Therefore, based on the above studies and both complex network and evolutionary game theories, in this paper, we construct an evolutionary game model of the collaborative innovation network members that considers government subsidies and supervision policies and simulates the evolution of collaborative innovation networks. We investigate in depth the main factors and mechanisms that influence the evolution and stability of collaborative innovation networks and then provide theoretical and practical advices.

3. Research Method

3.1. Evolutionary Game Model

3.1.1. Basic Assumptions of the Evolutionary Game Model. Before we construct the evolutionary game model between innovation network members, we must give the assumptions.

Assumption 1. Resource complementarity, risk sharing, and benefit sharing promote the successful realization of collaborative innovation. Members of a collaborative innovation network have complementary relationships. When faced with common problems, enterprises want to seek and establish collaborative innovation relations with other members in the network.

Assumption 2. Members of the network can choose from two strategies: implementing or abandoning collaborative innovation. No matter which strategy they choose, their aims are to maximize their own interests.

Assumption 3. Enterprises are assumed to have limited rationality in the decision-making processes. They seek better choices through continuous trial and error in learning and imitation and they constantly adjust their choices after comparing with other members of the network.

Assumption 4. The enterprises in the network are assumed to have the same absorption ability. When collaborative innovation is achieved, solving common problems can increase the total revenue, which will be distributed by the members of the collaborative relationship.

Assumption 5. In the process of making choices, one of the members may choose to abandon collaborative innovation because of other interests, which will bring economic losses

TABLE 1: Payment matrix of innovation network members.

		Enterprise 1	
		Implement collaborative innovation	Abandon collaborative innovation
Enterprise 2	Implement collaborative innovation	$R_1 + aVR - (1 - b)(C_1 + C'_1);$ $R_2 + (1 - a)VR - (1 - b)(C_2 + C'_2)$	$R_1 + rVR - (1 - b)(C_1 + C'_1);$ $R_2 + R'_2 - rVR - (1 - b)C_2 - P$
	Abandon collaborative innovation	$R_1 + R'_1 - rVR - (1 - b)C_1 - P;$ $R_2 + rVR - (1 - b)(C_2 + C'_2)$	$R_1; R_2$

to the collaborative innovation network and the other members in the cooperation. The enterprise that abandons the collaboration needs to pay compensation to the coinnovative enterprise.

Assumption 6. In China, subsidies and supervision are the main government measures to promote collaborative innovation. In this paper, subsidies are assumed as the positive incentive measure to help enterprises construct and maintain collaborative innovation relationships. By contrast, supervision is assumed as the negative one, which means an enterprise that betrays the collaborative relationship needs to pay fines to the coinnovative enterprise.

3.1.2. Notation. (1) $R_i (i = 1, 2)$ is the revenue of Enterprise 1 or 2 when each of them chooses to abandon collaborative innovation. The value of $R_i (i = 1, 2)$ can be positive or negative. If its value is positive, innovation activities have brought more profits to enterprises; if its value is negative, innovation has brought economic losses to enterprises.

(2) $C_i (i = 1, 2)$ is the cost of the initial construction of the collaborative relationship between Enterprise 1 and 2, while $C'_i (i = 1, 2)$ is the cost of maintaining the relationship.

(3) VR is the net profit of collaborative innovation, which means that it is the difference between the benefits and costs of collaborative innovation. A positive value indicates that collaborative innovation has brought more economic benefits; a negative value indicates that collaborative innovation has led to economic losses. When both of the enterprises choose to implement collaborative innovation, they distribute VR . The share of Enterprise 1 is aVR , while the share of Enterprise 2 is $(1 - a)VR$.

(4) r is the compensation coefficient, indicating the enterprise that chooses to abandon collaborative innovation needs to pay rVR to the coinnovative enterprise. In addition, the enterprise that abandons collaborative innovation can gain benefits from other places, and we assume these benefits as $R'_i (i = 1, 2)$.

(5) b is the subsidy coefficient, which reduces the costs of construction and maintenance of collaborative innovation. P is the fine that the enterprise that betrays the collaborative relationship needs to pay.

Based on the above assumptions and notations, the network member payment matrix based on evolutionary game theory [24] is shown in Table 1.

3.2. Equilibrium Analysis of the Evolutionary Game. Assume the probability that Enterprise 1 chooses to implement collaborative innovation is x and the probability that Enterprise 1 choose to abandon collaborative innovation is $(1-x)$. And assume that Enterprise 2 chooses y probability to implement collaborative innovation and choose $(1-y)$ probability of abandoning collaborative innovation. According to the game matrix (Table 1), the expected revenue of Enterprise 1 choosing to implement collaborative innovation is

$$\begin{aligned} U_{E1} &= y \left[R_1 + aVR - (1 - b)(C_1 + C'_1) \right] \\ &\quad + (1 - y) \left[R_1 + rVR - (1 - b)(C_1 + C'_1) \right] \quad (1) \\ &= (a - r)VRy + R_1 + rVR - (1 - b)(C_1 + C'_1) \end{aligned}$$

The expected revenue of Enterprise 1 choosing to abandon collaborative innovation is

$$\begin{aligned} U_{S1} &= y \left[R_1 + R'_1 - rVR - (1 - b)C_1 - P \right] \\ &\quad + (1 - y)R_1 \quad (2) \\ &= \left[R'_1 - rVR - (1 - b)C_1 - P \right] y + R_1 \end{aligned}$$

Similarly, the expected revenue of Enterprise 2 choosing to implement collaborative innovation is

$$\begin{aligned} U'_{E2} &= x \left[R_2 + (1 - a)VR - (1 - b)(C_2 + C'_2) \right] \\ &\quad + (1 - x) \left[R_2 + rVR - (1 - b)(C_2 + C'_2) \right] \quad (3) \\ &= (1 - a - r)VRx + R_2 + rVR - (1 - b)(C_2 + C'_2) \end{aligned}$$

The expected revenue of Enterprise 2 choosing to abandon collaborative innovation is

$$\begin{aligned} U'_{S2} &= x \left[R_2 + R'_2 - rVR - (1 - b)C_2 - P \right] + (1 - x)R_2 \quad (4) \\ &= \left[R'_2 - rVR - (1 - b)C_2 - P \right] x + R_2 \end{aligned}$$

The evolution process of the two members' decision-making can be shown with these replicator dynamic equations:

$$\begin{aligned}
\frac{dx}{dt} &= x(1-x) \left\{ [aVR - R'_1 + (1-b)C_1 + P] y \right. \\
&\quad \left. + rVR - (1-b)(C_1 + C'_1) \right\} \\
\frac{dy}{dt} &= y(1-y) \left\{ [(1-a)VR - R'_2 + (1-b)C_2 + P] x \right. \\
&\quad \left. + rVR - (1-b)(C_2 + C'_2) \right\}
\end{aligned} \tag{5}$$

$$\left[\begin{array}{cc}
(1-2x) \{ [aVR - R'_1 + (1-b)C_1 + P] y + rVR - (1-b)(C_1 + C'_1) \} & x(1-x) [aVR - R'_1 + (1-b)C_1 + P] \\
y(1-y) [(1-a)VR - R'_2 + (1-b)C_2 + P] & (1-2y) \{ [(1-a)VR - R'_2 + (1-b)C_2 + P] x + rVR - (1-b)(C_2 + C'_2) \}
\end{array} \right] \tag{6}$$

Using the determinant and the trace of the Jacobian matrix to analyze the stability of the evolution system, we get the following cases.

Case 1. When $rVR - (1-b)(C_1 + C'_1) < 0$ and $rVR - (1-b)(C_2 + C'_2) < 0$, $(0, 0)$ is the ESS (Evolutionary Stable Strategy). When the compensation gained from the enterprise who quit halfway is less than the costs of establishing and maintaining the relationships, both members will eventually choose to abandon collaborative innovation.

Case 2. When $(a+r)VR - R'_1 - (1-b)C'_1 + P < 0$ and $rVR - (1-b)(C_2 + C'_2) > 0$, $(0, 1)$ is the ESS. In this case, Enterprise 2 will choose to implement collaborative innovation and Enterprise 1 will choose to implement it. $rVR - (1-b)(C_2 + C'_2) > 0$ means the compensation received by Enterprise 2 from Enterprise 1 is greater than the costs in the collaboration. Therefore, regardless of the strategy chosen by Enterprise 1, Enterprise 2 tends to choose collaborative innovation. $(a+r)VR - R'_1 - (1-b)C'_1 + P < 0$ can be converted to $aVR - (1-b)C'_1 < R'_1 - rVR - P$. $aVR - (1-b)C'_1$ indicates the differences between the revenue of Enterprise 1 allocated in the collaborative innovation and the actual costs of maintaining the relationship, which reflects the net benefits that Enterprise 1 can obtain in the innovation. $R'_1 - rVR - P$ means the number of benefits that Enterprise 1 gains from other places when choosing to abandon collaboration minus the compensation paid to Enterprise 2 and the government's fine, which reflects the net income of Enterprise 1 when abandoning collaborative innovation.

Case 3. When $rVR - (1-b)(C_1 + C'_1) > 0$ and $(1-a+r)VR - R'_2 - (1-b)C'_2 + P < 0$, $(1, 0)$ is the ESS. It indicates that Enterprise 1 will choose to implement collaborative innovation and Enterprise 2 will choose to abandon collaborative innovation. Similar to the analysis of Case 2, the compensation received by Enterprise 1 from Enterprise 2 is higher than Enterprise 1's actual costs of establishing and maintaining the relationship. When this condition is met, regardless of the strategy chosen by Enterprise 2, Enterprise 1 will not have economic losses in the collaborative innovation, so Enterprise 1 will eventually choose to collaborate. The net income of Enterprise 2 in the collaborative innovation with Enterprise 1 is less than

Therefore, the strategy evolution of the two innovation network members can be described by the different equation systems in (5). The stable point of the system is analyzed, and five equilibrium points, $(0, 0)$, $(0, 1)$, $(1, 0)$, $(1, 1)$, and $((1-b)(C_2 + C'_2) - rVR) / ((1-a)VR - R'_2 + (1-b)C_2 + P)$, $((1-b)(C_1 + C'_1) - rVR) / (aVR - R'_1 + (1-b)C_1 + P)$ are obtained. Based on the literature [25], the Jacobian matrix of the different equations in (5) is

the earnings gained from other places if Enterprise 1 quit halfway, so Enterprise 2 will finally abandon the collaborative innovation.

Case 4. When $(a+r)VR - R'_1 - (1-b)C'_1 + P > 0$ and $(1-a+r)VR - R'_2 - (1-b)C'_2 + P > 0$, $(1, 1)$ is the ESS. Only when both conditions are met will Enterprise 1 and Enterprise 2 choose to implement collaborative innovation, which is also an ideal state of evolution.

3.3. Evolution Mechanism in the Context of BA Scale-Free Networks. We used a BA scale-free network to model a collaborative innovation network [26, 27]. Following the growth and preferential attachment model [28], we built a collaborative innovation network $G(V, E)$, in which V represents a collection of all members in a collaborative innovation network and E stands for collaborative relationships between the members. Assume that the influence of all the network members is mutual; that is, all the connected edges are undirected, and that there is at most one connecting edge between two members. If there is a connection between Enterprise i and j, it means that there is a direct game between the two members, which is expressed as $e_{ij} = 1$. If there is no connecting edge between the two members, it means that there is no game process between them, which is shown as $e_{ij} = 0$. There are m_0 innovation members in the initial collaborative innovation network. According to the "Matthew Effect" in complex networks, innovation members who have just joined are more likely to connect with members with larger degrees. The collaborative innovation network newly added n innovation members connect with the existing m ($m < m_0$) members as the probability of $p(k_i)$ until the number of members in the network no longer increases, forming the network $G(V, E)$, in which

$$p(k_i) = \frac{k_i}{\sum_j k_j} \tag{7}$$

In the collaborative innovation network, the member randomly selects a neighbor for revenue comparison and accumulates revenue in the process. Then the member will make the strategy conversion using a certain function based on the difference of revenues between the two members. For this paper we used the Fermi Rule to represent the function

TABLE 2: Values of Fixed Parameters in the Payment Matrix.

Parameter	R_1	R_2	R'_1	R'_2	$C_1 \& C_2$	$C'_1 \& C'_2$
Value	20	15	5	5	3	1.5

of this kind of conversion [29]. That is, the members in the network can learn and update their strategies according to the dynamic income situation during the game process. The update rule is to randomly select an enterprise from the neighbors in the network and imitate and learn the neighbor's strategy in the probability of W , which is

$$W_{S_i \leftarrow S_j} = \frac{1}{1 + \exp [U_i - U_j/k]} \quad (8)$$

U_i and U_j represent revenues of both members in the current round of the game. S_i and S_j represent the strategies of both members in the current round. The parameter k describes the environmental noise factor and characterizes the members' irrational choices, which means the probability that a member still does not change the strategy when the benefits of adopting the current strategy are lower than those for adopting the other. The closer k is to 0, the more rational the enterprise's choice. Strategy updates are strictly based on revenue comparison. When k approaches infinity, the members are in a noisy environment and are unable to make rational decisions but only random updates to their own strategies.

For this paper we use the reconnection mechanism of the broken edges in the network. The edges between the members reconnect once after the comparison of revenues in the game. At each step we select a node from the network with a positive exponential probability of the node's degree, randomly select one of the connections of the node, and then select another node to connect with the preference of positive exponential of the node's degree. The larger the nodes, the more likely are new connections, which is more suitable for real situations in which important members of larger innovation networks can link with other members and establish collaborative relationships easily.

4. The Simulation and Discussion

4.1. Parameter Initialization Setting. In order to set the simulation parameters reasonably and ensure the reliability and scalability of the research conclusions, we consulted 16 experts, majors in the field of management science and simulation research in China, by e-mail, telephone conversation, and in-person meeting; there were seven professors and nine associate professors. The experts suggested setting relevant parameters based on the realities of the collaborative innovation networks as follows.

- (1) The distribution of income is very important for the stable development of collaborative innovation networks, which can be reflected by setting the parameters for one side of the collaborative innovation network members. The experts pointed out that it is

reasonable to use 0.5 for the case of profit sharing, 0.2 and below for abnormal distribution of benefits, and more than 0.2 but less than 0.5 to indicate distribution according to contribution.

- (2) The enterprise that abandons collaborative innovation shall pay compensation to the innovation partner. Due to the heterogeneity of collaborative innovation activities, the compensation would be related to the expected benefits. Experts suggested that it can be reflected by the coefficient of compensation and that half of the estimated revenue can be set as the maximum amount of compensation.
- (3) In China, the government's subsidies for collaborative innovation are reflected in project approvals. Due to the heterogeneity of the subsidized projects, the subsidy coefficient is used to reflect this part of funding, which can reduce the input of the collaborative innovation. In addition, the government's standards are generally similar, so the amount of fine could be set to directly reflect this kind of regulatory measures. The experts recommended that we use the method of valuating several units in economics (such as 2 unit returns) to assign fixed parameters in the payment matrix.

In this paper, we select the values of parameter of simulation with the approval of the most experts within the range of parameter values they suggested. The number of small network members is set to 50, and the number in the large network is 2000. The collaborative innovation revenue is set in the range of 8-12, and the revenue distribution ratio is set within 0.1-0.5; the compensation coefficient range is also 0.1-0.5. The collaborative innovation relationship initial construction cost range is 3-9, and the relationship maintenance cost range is 1-3. The subsidy coefficient ranges from 0 to 0.25, and the penalty range for the supervision is 0.5-1.0. To simulate the influence of factors on network evolution results and speed, the game steps in the network were set to be 100 by referring to the relevant studies of Xia Cao and Lupeng Zhang [30]. The number of game steps was not exactly the same as these but is related to the times of games in reality and the evolution results can have reference value to the real collaborative network evolution values of other fixed parameters are shown in Table 2.

4.2. Numerical Simulation and Discussion

4.2.1. The Effect of Collaborative Innovation Revenue. In the small network (Figure 1), when VR is 8, the network will disintegrate; when VR is 9 or more, the network will tend to be stable, and the network members will continue to implement collaborative innovation. However, in the large

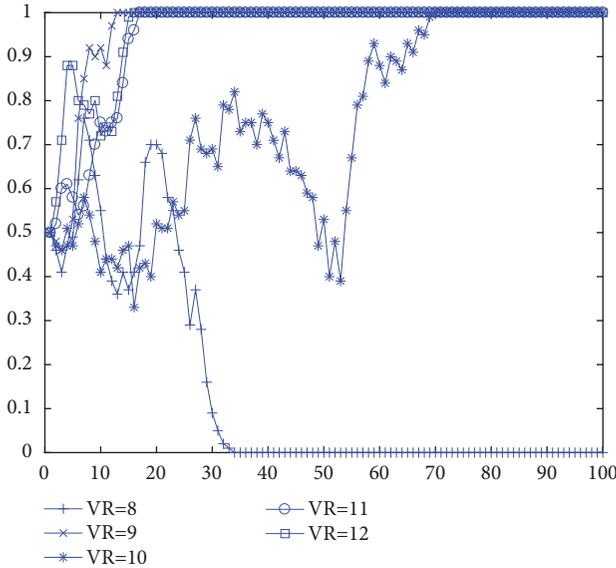


FIGURE 1: The impact of revenue on a small network.

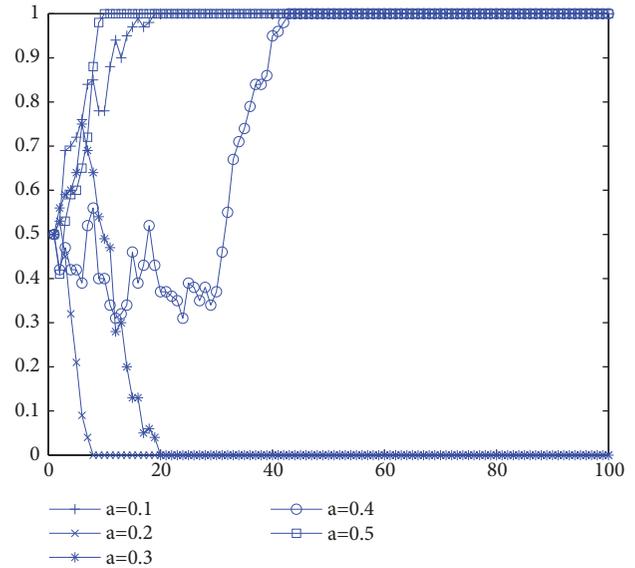


FIGURE 3: The impact of revenue distribution on a small network.

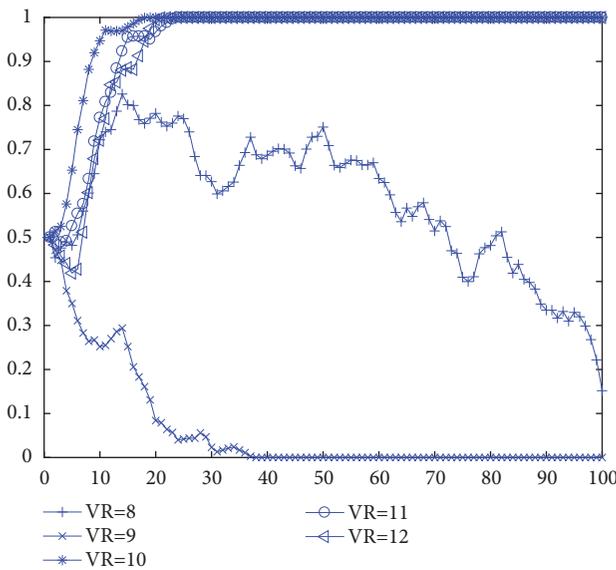


FIGURE 2: The impact of revenue on a large network.

network (Figure 2), when the VR is 8 or 9, the network will disintegrate, but when it is 10 or higher, it will continue to stabilize. Therefore, we find that the increase of collaborative innovation revenue stimulates the network members to choose collaborative innovation; that is, increasing the collaborative innovation revenue can enhance the positive evolution of the network. Moreover, collaborative innovation revenue benefits smaller networks more obviously. Thus, in collaborative innovation networks in the beginning stage (such as China's Bohai Bay National New District), policies such as subsidies can be used to reduce the cost and risk of collaborative innovation and increase revenue among members.

4.2.2. The Effect of Revenue Distribution. Change revenue distribution coefficient a from 0.1 to 0.5 to analyze its impact on the network evolution. Looking at Figure 3, we can see that the impact of revenue distribution on network evolution is nonlinear. When a is 0.1, 0.4, or 0.5, the small network can achieve continuous stable collaborative innovation, but the network will eventually disintegrate when the value is 0.2 or 0.3. It can be inferred that in small networks, equal or near-equal innovation gains among innovation network members contribute to the stability of the network. It is worth noting that when the revenue distribution between members is abnormally uneven ($=0.1$), it can also promote the network to evolve to a stable status where all members will implement collaborative innovation because when the revenue distribution is abnormally uneven, it is generally the case that the partners' strengths are very different; the weaker members will give up some economic benefits in order to establish long-term, stable collaborative relationships. However, the impact of revenue distribution on the large network has different results (Figure 4). When the distribution is equal or abnormally uneven (0.1 or 0.5), the network will disintegrate, but when the distribution parameter is 0.2, 0.3 or 0.4, that is, when there is a small difference in distribution between the partners, the network will evolve to stable collaboration.

4.2.3. The Effect of Compensation Mechanism. The compensation coefficient r changes from 0.1 to 0.5. Figure 5 displays that when the compensation coefficient is 0.1, 0.2, or 0.3, all the members in the network will eventually abandon collaborative innovation, causing the network to disintegrate. When the coefficient increases to 0.4 and above, the network evolves into stable collaborative innovation. The compensation coefficient has no significant effect on the speed of small network evolution. Figure 6 shows that when r is 0.1 or 0.2, the network disintegrates. When r is 0.3, the proportion of network members who continue to

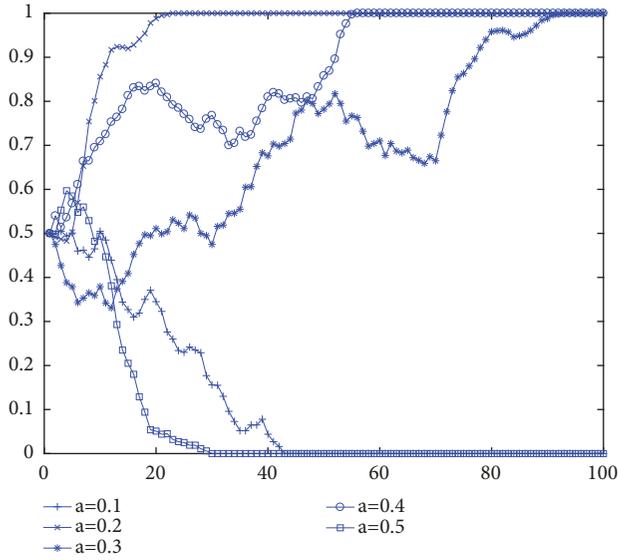


FIGURE 4: The impact of revenue distribution on a large network.

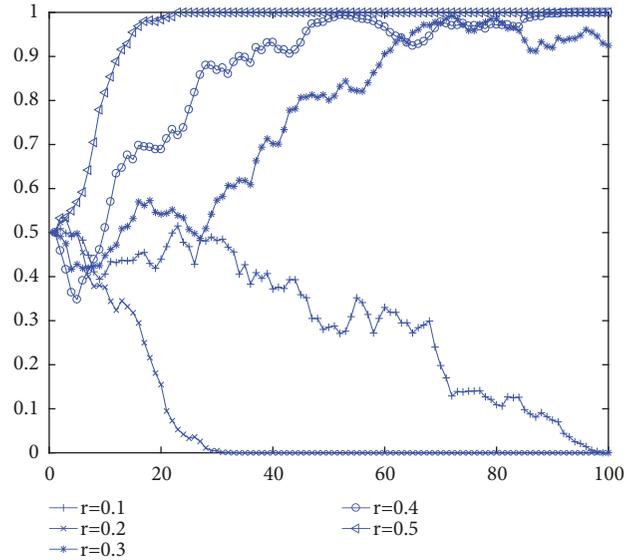


FIGURE 6: The impact of compensation on a large network.

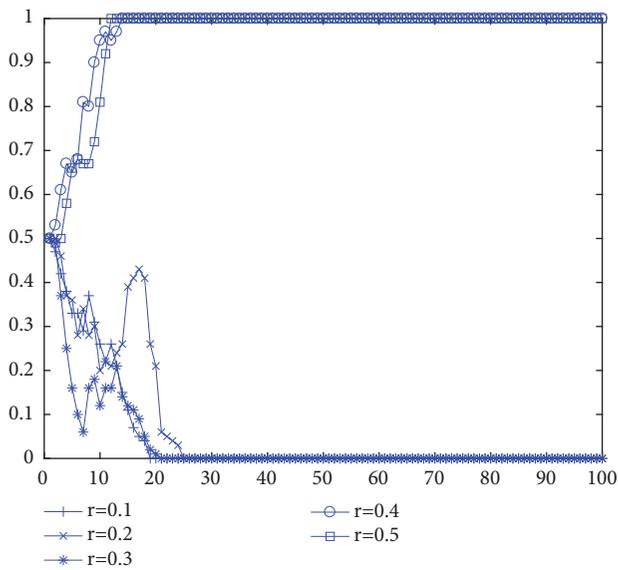


FIGURE 5: The impact of compensation on a small network.

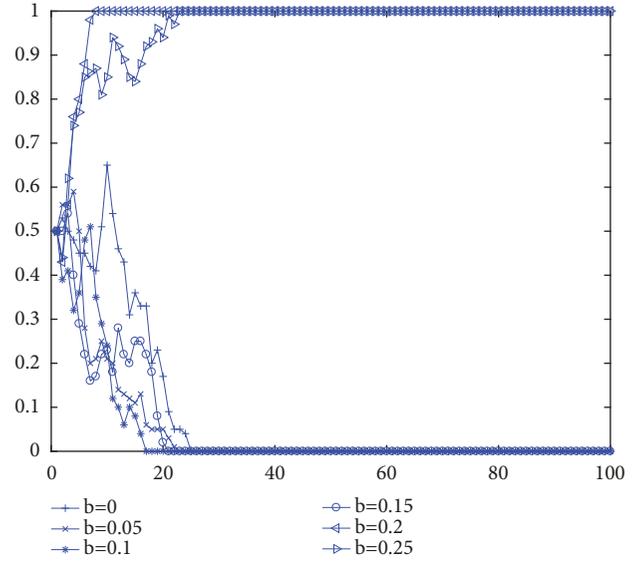


FIGURE 7: The impact of subsidies on a small network.

implement collaborative innovation fluctuates within a range of more than 0.9 but less than 1.0, which indicates that when the compensation is moderate, most members will choose collaborative innovation under the influence of others in the network, but a few will still wait and hesitate. When r is 0.4 or 0.5, the network can evolve to a steady state of continuous collaboration. In summary, whether networks are small or large in scale, increasing the compensation coefficient will promote the evolution of the innovation network to stable, continuous synergy. Additionally, the driving forces for large networks are more obvious than are those for small networks.

4.2.4. The Effects of Subsidies. For this paper we chose subsidy coefficients b of 0, 0.05, 0.1, 0.15, 0.2, and 0.25. When b

is 0, it means there are no subsidies. Figure 7 shows the evolution process of the small network, particularly that when the government does not provide subsidies, the network disintegrates; even when the government gives financial support and the subsidy coefficient is 0.05, 0.1, or 0.15, the innovation network still breaks down. Not until the subsidy coefficient increases to 0.2 or above does the network evolve to a stable, continuous collaborative innovation status. However, analyzing Figure 8, which shows the evolution of the large network, reveals that when the government provides financial support and the subsidy coefficient is 0.05, the ideal situation of continuous collaborative innovation can be realized. This is because the subsidies in this paper are for establishing and maintaining collaborative innovation relationships. In large innovation networks, members need to consume relatively

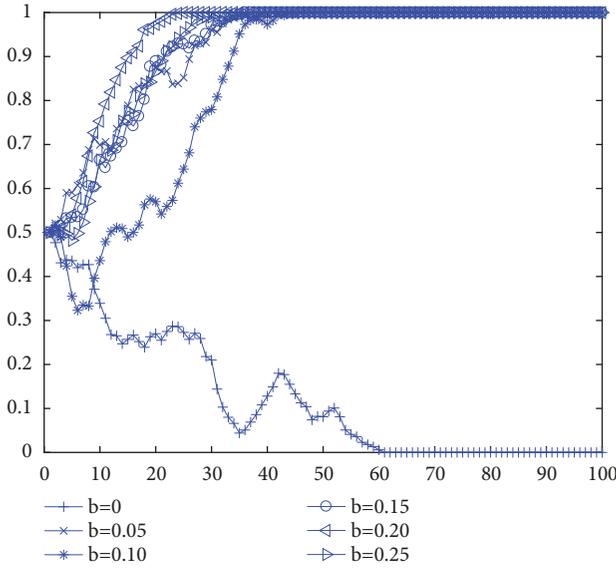


FIGURE 8: The impact of subsidies on a large network.

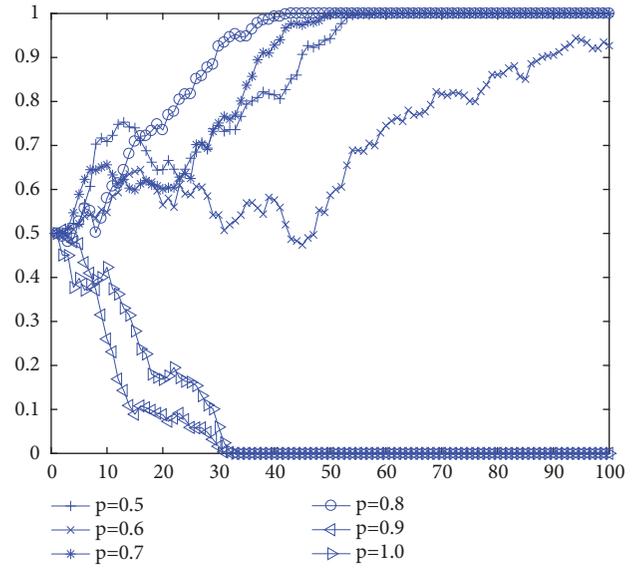


FIGURE 10: The impact of supervision on a large network.

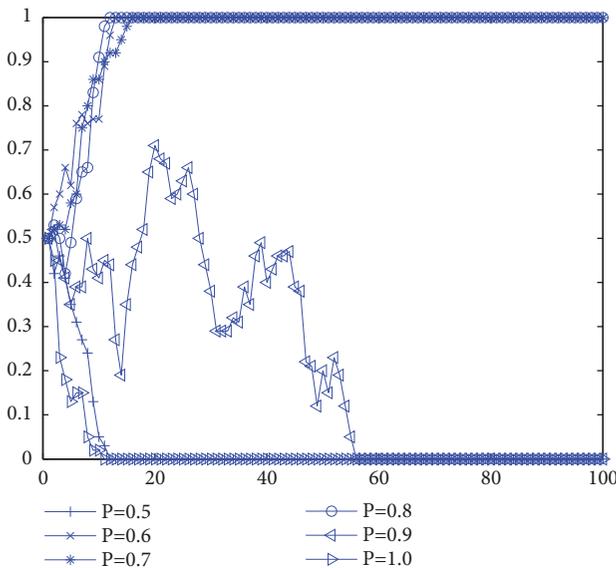


FIGURE 9: The impact of supervision on a small network.

more time and other resources when looking for partners. Thus, once a relatively stable relationship is established, it will not be easily disbanded.

4.2.5. The Effect of Supervision Policy. Except for supervision, we also used penalties to reflect supervision and set P in the range of 0.5 to 1.0. The results for the evolution of the small network are shown in Figure 9, and those for the large network are shown in Figure 10. It is inferred that when the penalty is low (P is 0.5) or the penalty is very high (P is 0.9 or 1.0), the small network will eventually disintegrate; When the penalty is moderate (P is 0.6, 0.7, or 0.8), the small network can evolve to the steady state of continuous collaborative innovation. Different from the evolution results

for the small network, When P is 0.5, 0.6, 0.7, and 0.8, the large network continues to evolve to the stable collaborative innovation status. The large network disintegrates when P is 0.9, and 1.0. In summary, we can infer that increasing the penalty will help promote the mature and stable development of the collaborative innovation network. With government supervision, the stability of the relationships among the collaborative innovation network members can be strongly guaranteed; not only is the risk reduced from one member's choosing to abandon the collaboration halfway, even if one member chooses to give up, the other can have economic gains to make up for the loss. However, excessive punishment will hinder the realization of collaborative innovation in the network because in collaboration, network members bear risks, and there is the possibility of finding a better partner halfway. If the punishment of betrayal is too high, the network member will be more cautious in deciding whether or not to implement collaborative innovation, which will impede the development of the innovation network. In addition, the sensitivity of different network sales to penalties varies; the setting of in penalty in large networks should be broad, and the scope of punishment in small networks should be stricter.

4.2.6. The Combinational Effect of Revenue Distribution and Compensation. To investigate the influence of revenue distribution and compensation mechanisms on collaborative innovation network evolution, the value of revenue distribution coefficient a is set to 0.2 to represent an uneven distribution or 0.5 to represent an average distribution. The compensation coefficient r is set to 0.2 to represent a low level of compensation for midway betrayal and 0.5 represents a high level of compensation. Let a and r take different values to investigate the influence of distribution and compensation mechanisms on the evolution of a collaborative innovation network. Figure 11 shows the results of small-scale network evolution and Figure 12 shows those of large-scale network

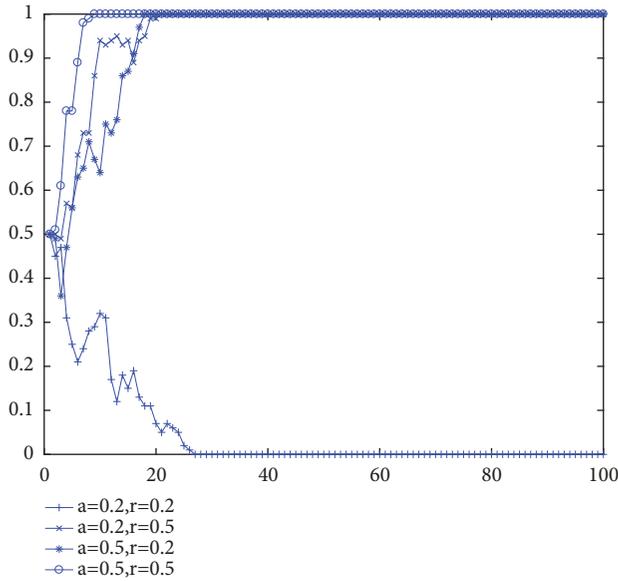


FIGURE 11: The impact of revenue distribution and compensation on a small network.

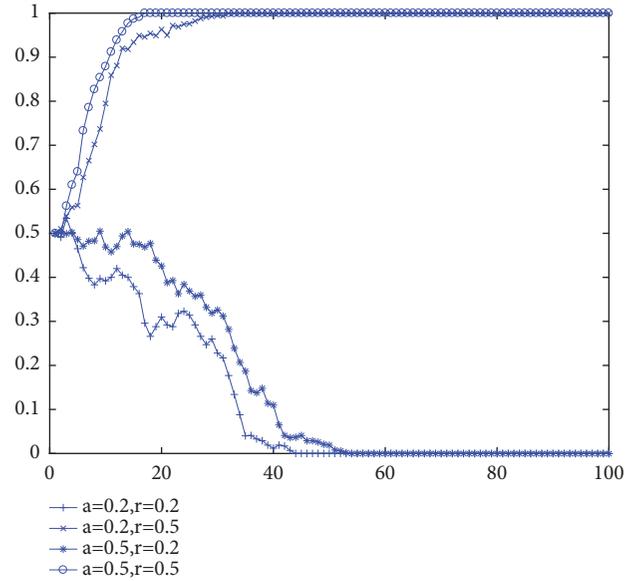


FIGURE 12: The impact of revenue distribution and compensation on a large network.

evolution. As can be seen from Figure 11, when the distribution of innovation benefits is unbalanced ($a = 0.2$) and the compensation degree is low ($r = 0.2$), the collaborative network will eventually collapse, but when the compensation coefficient is increased to 0.5, the network can be sustainable and stable. When the distribution of innovation benefits is balanced ($a = 0.5$), a compensation coefficient of either 0.2 or 0.5 can ensure the network's continuous and stable development. Compared to the single-factor result of the distribution mechanism in Figure 3, the compensation mechanism can make up for the negative impact of the uneven income distribution on network evolution, but it can only be realized by increasing the compensation level to a higher level. In large-scale networks, the network's continuous evolution cannot be maintained regardless of the average distribution of benefits when the compensation for midway betrayal is at a low level. Only when the compensation for midway betrayal is at a high level can the network continue to be stable. In conclusion, the influence of revenue distribution and compensation of midway betrayal on the evolution of innovation network evidently has a great relationship with the network scale. In a small network, a high level of compensation can be set up to compensate for unbalanced income distribution. However, in large-scale networks, compensation for midway betrayal is more important than revenue distribution for the network's continued stability.

4.2.7. The Combinational Effect of Subsidies and Supervision.

To investigate the combinational impact of subsidy and supervision on network evolution, coefficient b is set to 0.05 to indicate a low level of subsidy, 0.25 to indicate a high level of subsidy, and p is set to 0.5 or 1.0 to represent a low level or high level of supervision, respectively. Upon combining the implementation efforts of the two policies

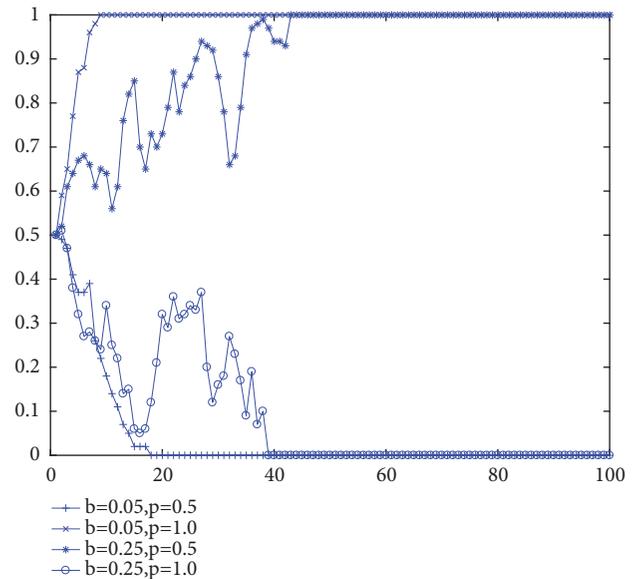


FIGURE 13: The impact of subsidies and supervision on a small network.

to explore their influences on the evolution of different-scale networks, Figure 13 shows the results of small-scale networks, and Figure 14 shows that of large-scale networks. As shown in Figure 13, even when the subsidy is small, a low level of supervision still cannot reverse network dissolution, while a high level of supervision can guarantee a network's continuous stability. When subsidies are large, high levels of regulation can negatively affect network evolution. In large-scale networks, a high level of regulation can improve the stability of network evolution under low-level subsidy policy, but it is not as strong as that in small-scale networks. With a high level of subsidies, both low and high supervision

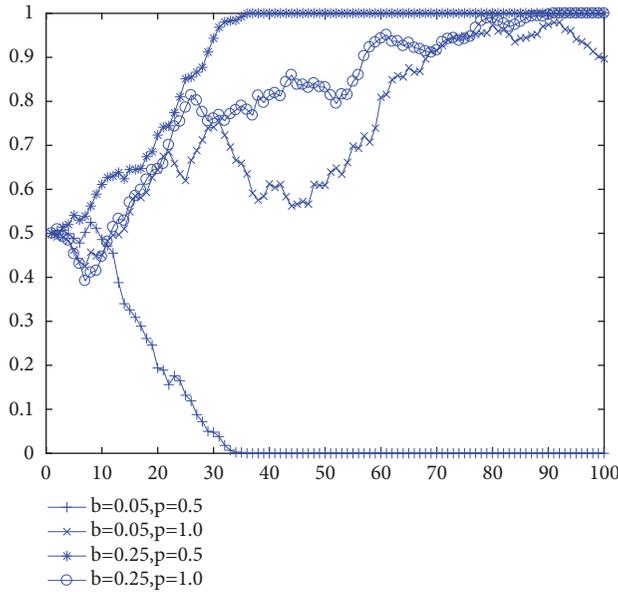


FIGURE 14: The impact of subsidies and supervision on a large network.

can promote the network's continuous stability, but high supervision can slow down the speed with which the network reaches a stable state. This shows that compared to small-scale networks, the large number of participants in large-scale networks mean that both the supplementary effect of supervision policies on low-level subsidy policies and the blocking effect on high-level subsidy policies are weakened. In summary, at a high level of subsidies, the government can weaken the supervision of defectors. No matter the network's size, supervision policies have a supplementary effect on the low level of subsidies, but the government needs to improve the supervision strength to promote the network's continuous stability, and the supervision strength for large-scale networks should be stronger than that of small-scale networks.

5. Conclusions

Based on the theory of collaborative innovation and complex network theory, with this paper, we first analyze the game process between members of collaborative innovation networks and then construct two different scales of BA networks. Finally, we use simulation to study the influence mechanism of collaborative innovation revenue, revenue distribution, compensation coefficient, and government incentive policies on the evolution of collaborative innovation networks. The results show that

(1) When the difference between the distributed interest and the actual maintenance cost is larger than the difference between the income obtained from others when members quit halfway and the compensation paid to their partners added to the penalty paid to the government, network members should choose to implement collaborative innovation. In this situation, collaborative partners will also choose

to implement collaborative innovation driven by economic interests, which will promote sustainable and stable cooperative relations. Otherwise, they should choose to abandon collaborative innovation to prevent losses. Therefore, the benefit distribution mechanism, the cost of the collaborative innovation, the compensation mechanism of betrayal, and the government's subsidies and supervision will have important impacts on the innovation network members' decisions and behavior.

(2) Collaborative innovation revenue and distribution mechanism have significant impacts on the evolution of collaborative innovation networks. The increase in innovation revenue can promote continuous collaboration, and the benefits to small networks are more obvious. In small networks, cultivating and introducing innovation leaders should receive more focus. It is also necessary to pay attention to the rationality of the revenue distribution when the members of small networks have roughly the same strengths in order to promote the continuous synergy of the network members. As the scale of the network grows, the role of innovation leaders in the network is weakened. In addition to strengthening the objective evaluation of the value of innovation, it is also necessary to allocate innovation revenue according to the continuous contributions of network members to encourage all network members to work as diligently as possible in the process of collaborative innovation. Then the networks will gradually evolve to a coordinated and stable state.

(3) Reasonable compensation mechanisms can effectively promote the stable evolution of collaborative innovation networks, and these benefits are more obvious for large networks than for small ones. Therefore, in practice, when the innovation network partners establish collaborative relationships, their behaviors can be restrained by increasing the compensation to the traitor. Especially in large networks, establishing compensation mechanisms can effectively maintain stable collaborative innovation, whereas if the compensation is difficult to achieve under the market mechanism, the government needs to implement regulatory measures to force the betrayers to pay the fines.

(4) When revenue distribution and compensation mechanisms work together on different scale networks, their dominant positions differ. Revenue distribution plays a dominant role in small-scale networks and the realization of the balanced distribution of benefits is an important driving force to promote the network's continuous stability. However, if a balanced distribution cannot be realized, increasing the compensation of midway defectors can stabilize a cooperative relationship. In a large-scale network, the compensation mechanism of a midway betrayer is the dominant factor that affects the network's stability and should receive attention.

(5) Government subsidies and supervision contribute positively to the continued stability of collaborative innovation networks. Subsidies have weaker effects on small networks, and they need to be increased to play the catalytic role; on the contrary, the benefits of subsidies to large networks are clearly effective. Large networks have stricter requirements on the scope of supervision, and too weak or too strong supervision will lead to the disintegration of the network. In contrast, small networks require more general

supervision intensity, and moderate intensity can promote stable and collaborative evolution. To ensure the continuous and stable evolution of the collaborative innovation network, when the government can afford to pay a high level of subsidies, the supervision and punishment of midway defectors should be weakened. When the government can only provide a low level of subsidies, we should strengthen the supervision of members to reduce the occurrence of betrayal and the supervision of large-scale network members should be stronger than small-scale network.

Several limitations exist in this paper, which will be the focus of future research. First, firms have various absorptive capacities, which will cause different evolution results in collaborative innovation networks. We did not consider this in this paper due to the limitations of the model setting. In the future, we will use other research methods such as survey investigation and Structural Equation Models to explore the influence of firms' absorptive capacities on the evolution of a collaborative innovation network. Second, we have presented some assumptions before building the evolutionary game model and have invited several experts and entrepreneurs to refine our research model and assign parameters to make the research model and conclusions as close to reality as possible. However, some distance remains between our research and the real innovation network. Therefore, although this study can reflect government subsidies and supervisions that can intervene in the collaborative innovation network in some aspects, this is only based on theoretical research. In the future, we will use relevant panel data in China to study the performance of collaborative innovation policy and its impact on the development of collaborative innovation networks and further put forward suggestions for the improvement of collaborative innovation policy.

Data Availability

The data used to support the findings of this study are included within the article. All data included in this study are available upon citations.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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